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Search for the Decays $B^0_d \to \gamma\gamma$ and $B^0_s \to \gamma\gamma$

The L3 Collaboration

Abstract

A search for the decays $B^0_{d,s} \to \gamma\gamma$ in 2.95 million hadronic Z decays has been performed using the L3 detector at LEP. No candidates are found in the signal region and upper limits have been set on the branching ratios: $Br(B^0_d \to \gamma\gamma) < 3.9 \times 10^{-5}$ and $Br(B^0_s \to \gamma\gamma) < 14.8 \times 10^{-5}$ at 90% CL. These are the first limits set on these exclusive rare decays.

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Introduction

Measurements of rare B hadron decays are important discriminators to test the Standard Model (SM) as well as to probe the physics beyond it. Of particular interest are the decays $B^0_{d,s} \to \gamma\gamma$ for which there has been no experimental measurement until now. The decays correspond to a second order weak transition, including gluonic penguins, followed by annihilation, often referred to as an "effective" flavor-changing weak neutral current process, as shown by some diagrams in Figure 1. The expected branching ratio for this decay mode is $\sim 10^{-7}$ in the SM, although there are large theoretical uncertainties [1–4]. As pointed out by Falk [5] exclusive decay rates are extremely difficult to compute reliably. Observation of these decays could lead to a direct measurement of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $|V_{ts}|$ and $|V_{td}|$. In contrast to the theoretical situation, experimentally $B^0 \to \gamma\gamma$ is a relatively clean channel to study.

It is believed that for some non-standard scenarios, such as two-Higgs-doublets and minimal supersymmetric models, the $B^0 \to \gamma\gamma$ decay rate can be significantly enhanced [1]. Thus any observation of the decay $B^0 \to \gamma\gamma$ at an unusual rate could be an indication of new physics.

This analysis exploits the high resolution BGO electromagnetic calorimeter of the L3 detector which is well suited for this purpose. The analysis is performed on data recorded in 1991 through 1994 at $\sqrt{s} \approx M_Z$, corresponding to a sample of 2.95 million $e^+e^- \to$ hadron events. The mixed sample of B hadrons available in Z decays provides an opportunity to study B^0_s meson decays which are not accessible at the center-of-mass energy of the $\Upsilon(4S)$.

The L3 Detector

The L3 detector is described in detail in reference 6. It consists of a central tracking chamber, a high resolution electromagnetic calorimeter composed of bismuth germanium oxide (BGO) crystals, a ring of plastic scintillation counters, a uranium and brass hadron calorimeter with proportional wire chamber readout, and an accurate muon chamber system. These detectors are installed in a 12 m diameter magnet which provides a uniform field of 0.5 T along the beam direction.

The central tracking chamber is a time expansion chamber (TEC) with high spatial resolution in the r-ϕ plane normal to the beam. A chamber mounted just outside the TEC provides z-coordinate measurements.

The material preceding the barrel part of the electromagnetic calorimeter amounts to less than 10% of a radiation length. In this region the energy resolution of the BGO calorimeter is better than 2% for energies above 1 GeV. The angular resolution of electromagnetic clusters is better than 0.5° for energies above 1 GeV.

Event Selection

Hadronic events selected with a standard set of cuts [7] are used for this analysis. Candidate photons in an event are selected in the barrel electromagnetic calorimeter with $|\cos\theta| \leq 0.75$, where θ is the polar angle, and are recognized as isolated energy clusters in the electromagnetic calorimeter with a shower shape consistent with that of electromagnetic particles. To ensure that the electromagnetic cluster corresponds to a photon, there should be no charged track within 10 mrad of the electromagnetic cluster in the plane transverse to the beam direction.

We use JETSET [8] simulated b-flavor events, requiring the decay chain $B^0_{d,s} \to \gamma\gamma$, for one of the $B^0_{d,s}$ mesons. The mass of the B^0_d and B^0_s generated in the Monte Carlo are 5279 MeV and 5373 MeV respectively. The modified Peterson fragmentation function [9] is used as a function of $x_E = 2E_{hadron}/\sqrt{s}$ with the parameter $\epsilon_b = 0.05$. For the background studies a sample of approximately 2.1 million hadronic Z events were generated and simulated using the JETSET Monte Carlo program.

Due to the hard fragmentation of the b quark, the energy carried by the two photons from a B^0 decay is large. The sum of the two photon energies is required to be more than 25 GeV as shown in Figure 2a, where the combinatorial background is peaked at small energies in contrast to the $B^0 \to \gamma\gamma$ Monte Carlo events. In addition it is required that the opening angle between the two photons $\theta_{\gamma\gamma}$ be less than 40° as shown in Figure 2b. In this case the combinatorial background tends to be at large angles. These cuts reduce the combinatorial background either from the low energy photons or from the opposite hemisphere. The invariant mass of the $\gamma\gamma$ system is reconstructed with photons having a minimum energy of 2 GeV.

In order to separate $b\bar{b}$ events from other hadronic events, a multidimensional analysis based on a neural network approach described elsewhere [7] is used. It has been verified that the neural network response for $B^0_{d,s} \to \gamma\gamma$ has the same shape as for other $b\bar{b}$ events. The efficiency calculation is based on a full simulation of the L3 detector [10] allowing for the effects of energy loss, multiple scattering, interactions and decays in the detector material as well as time-dependent detector effects.

Figure 3(a,b) shows the $\gamma\gamma$ invariant mass of the $B^0_{d,s}$ Monte Carlo events. A Gaussian fit is performed on the invariant mass distributions for B^0_d and B^0_s separately. The mass resolutions obtained are $\sigma = 72$ MeV, which is to be compared with the mass difference $M_{B^0_s} - M_{B^0_d} = 94$ MeV. The efficiency for this process within the 2σ mass window of the $B^0_{d,s}$ is calculated to be $0.227 \pm 0.007 \pm 0.006$ using all preselected events and $0.118 \pm 0.005 \pm 0.007$ with the additional $b\bar{b}$ selection requirement based on the neural network, where the first error is statistical and the second is systematic. The systematic uncertainties are evaluated by varying the selection criteria and the fragmentation function as shown in Table 1.

Source	$\Delta\epsilon_{B^0 \to \gamma\gamma}$
Electromagnetic Shower Shape	± 0.0033
Track Veto	± 0.0028
Opening Angle $\theta_{\gamma\gamma}$	± 0.0005
Energy sum of the two photons	± 0.0018
$b\bar{b}$ Selection	± 0.0035
Fragmentation	± 0.0036
Total	± 0.0069

Table 1: Systematic uncertainties on the efficiency for $B^0 \to \gamma\gamma$ Monte Carlo events.

A $B^0 \rightarrow \pi^0\pi^0$ decay can fake a $B^0 \rightarrow \gamma\gamma$ decay, if π^0's are very energetic such that the two photons from π^0 decay merge into single cluster. We make the conservative assumption that the contribution $B^0 \rightarrow \pi^0\pi^0$ is negligible. Searches for $B^0 \rightarrow \pi^0\pi^0/\pi^0\eta/\eta\eta$ are described in reference 11.

Results

Figure 3(c,d) shows the invariant mass distribution of the $\gamma\gamma$ system for all events and for the $b\bar{b}$ enriched sample in data and five-flavor $Z \rightarrow q\bar{q}$ Monte Carlo events. As one can see from Figure 3c the shape of the background is well reproduced by the five-flavor $q\bar{q}$ Monte Carlo events. With the additional $b\bar{b}$ selection requirement based on the neural network, no candidates are observed within $\pm 2\sigma$ mass window of $B^0_{d,s}$ (see Figure 3d).

Upper limits on the exclusive branching ratio for the B^0_d and B^0_s mesons decaying into two photons are obtained using a binned likelihood fit to the $\gamma\gamma$ invariant mass distribution. The background is estimated from the shape of the invariant mass distribution in the data shown in Figure 3d. An exponential function is fitted to the invariant mass distribution in the range 4.4 GeV to 6.0 GeV, excluding the $B^0_{d,s}$ mass window. For the signal there are two components, corresponding to B^0_d and B^0_s. The overlapping region of B^0_d and B^0_s is taken into account using the Monte Carlo $\gamma\gamma$ mass distributions. The total likelihood function is given by:

$$\mathcal{L}(\mu_d, \mu_s) = \prod_{i=1}^{n} \frac{e^{-(\mu_{b,i}+\mu_{d,i}+\mu_{s,i})}(\mu_{b,i} + \mu_{d,i} + \mu_{s,i})^{N_i}}{N_i!}$$

where i is the bin number; N_i are the number of observed events in bin i; μ_b is the background component and μ_d, μ_s are the B^0_d and B^0_s signal components respectively. The total signal components are given by:

$$\mu_q = \sum_i \mu_{q,i} = \mathrm{Br}(B^0_q \rightarrow \gamma\gamma) \times N_h \times 2 \times R_{b\bar{b}} \times f_{b\rightarrow q} \times \epsilon_{B^0_q \rightarrow \gamma\gamma} \quad (\text{for} \quad q = d, s)$$

where N_h is the total number of hadronic Z decays, $R_{b\bar{b}}$ is taken from the L3 measurement [7], and $f_{b\rightarrow\ d,s}$ is the fraction of $b \rightarrow B^0_d = 39.5 \pm 4.0\%$ and $b \rightarrow B^0_s = 12.0 \pm 3.0\%$ used, in agreement with the available measurements [12], while $\epsilon_{B^0_q \rightarrow \gamma\gamma}$ denotes the selection efficiency for $B^0_{d,s} \rightarrow \gamma\gamma$.

The likelihood is evaluated as a function of the branching ratios $\mathrm{Br}(B^0_d \rightarrow \gamma\gamma)$ and $\mathrm{Br}(B^0_s \rightarrow \gamma\gamma)$, taking into account errors on the efficiency, $R_{b\bar{b}}$, $f_{b\rightarrow d,s}$ and the background parameterization. By varying $\mathrm{Br}(B^0_d \rightarrow \gamma\gamma)$ and $\mathrm{Br}(B^0_s \rightarrow \gamma\gamma)$ simultaneously we obtain the two dimensional likelihood distribution for different confidence levels. The one dimensional 90% confidence level upper limits on the B^0_d (B^0_s) branching ratios are obtained by integrating the likelihood over all the values of the B^0_s (B^0_d) branching ratios. The 90% confidence level limits obtained are

$$\mathrm{Br}(B^0_d \rightarrow \gamma\gamma) < 3.9 \times 10^{-5} \qquad \text{at} \ \ 90\% \ \ \text{CL},$$

$$\mathrm{Br}(B^0_s \rightarrow \gamma\gamma) < 14.8 \times 10^{-5} \qquad \text{at} \ \ 90\% \ \ \text{CL}.$$

A complementary analysis not relying on the neural network $b\bar{b}$ selection has been performed as a cross-check. This analysis uses photon selection and global kinematic variables similar to those used in reference 11. A single variable function based on a multidimensional approach has been used to discriminate the signal from the background events. This gives compatible results with the analysis described in this paper.

Conclusion

A search for the exclusive rare decays $B^0_{d,s} \rightarrow \gamma\gamma$ in 2.95 million hadronic Z decays has been performed. No candidates are observed in the data within the mass window of $B^0_{d,s}$. Upper limits on these decay modes have been set:

$$\mathrm{Br}(B^0_d \rightarrow \gamma\gamma) < 3.9 \times 10^{-5} \qquad \text{at} \;\; 90\% \;\; \text{CL},$$

$$\mathrm{Br}(B^0_s \rightarrow \gamma\gamma) < 14.8 \times 10^{-5} \qquad \text{at} \;\; 90\% \;\; \text{CL}.$$

The present results are the first limits set on the above branching ratios.

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Figure 1. Examples of possible diagrams responsible for the $B^0_{d,s} \to \gamma\gamma$ decay. In these diagrams $q = u$, c or t. H represents a possible charged Higgs particle.

Figure 2. Comparison of a) E_{Total}, the total energy of the two photons and b) $\theta_{\gamma\gamma}$, the opening angle between the two photons; for combinatorial background from data and five flavor $q\bar{q}$ Monte Carlo in contrast to exclusive $B^0 \to \gamma\gamma$ Monte Carlo events.

Figure 3. The measured $\gamma\gamma$ invariant mass distribution after all the selection cuts for the Monte Carlo a) $B^0_d \to \gamma\gamma$ and b) $B^0_s \to \gamma\gamma$ decays. The solid line is the result of a fit using a Gaussian function. The measured $\gamma\gamma$ invariant mass distribution for c) all events and d) the $b\bar{b}$ enriched sample, in data and Monte Carlo. The $b\bar{b}$ enriched sample is fitted with an exponential function excluding the $B^0_{d,s}$ mass window shown with dotted lines.

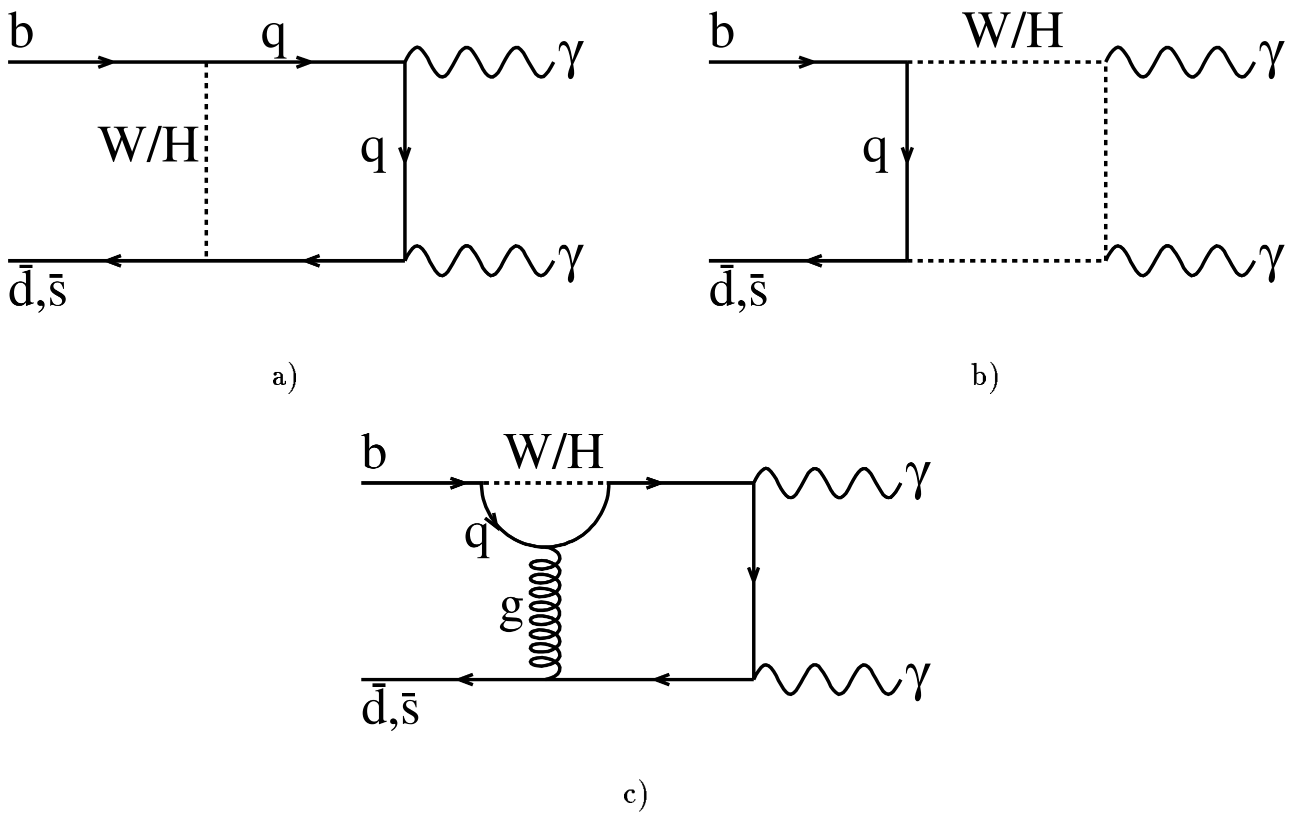


Figure 1

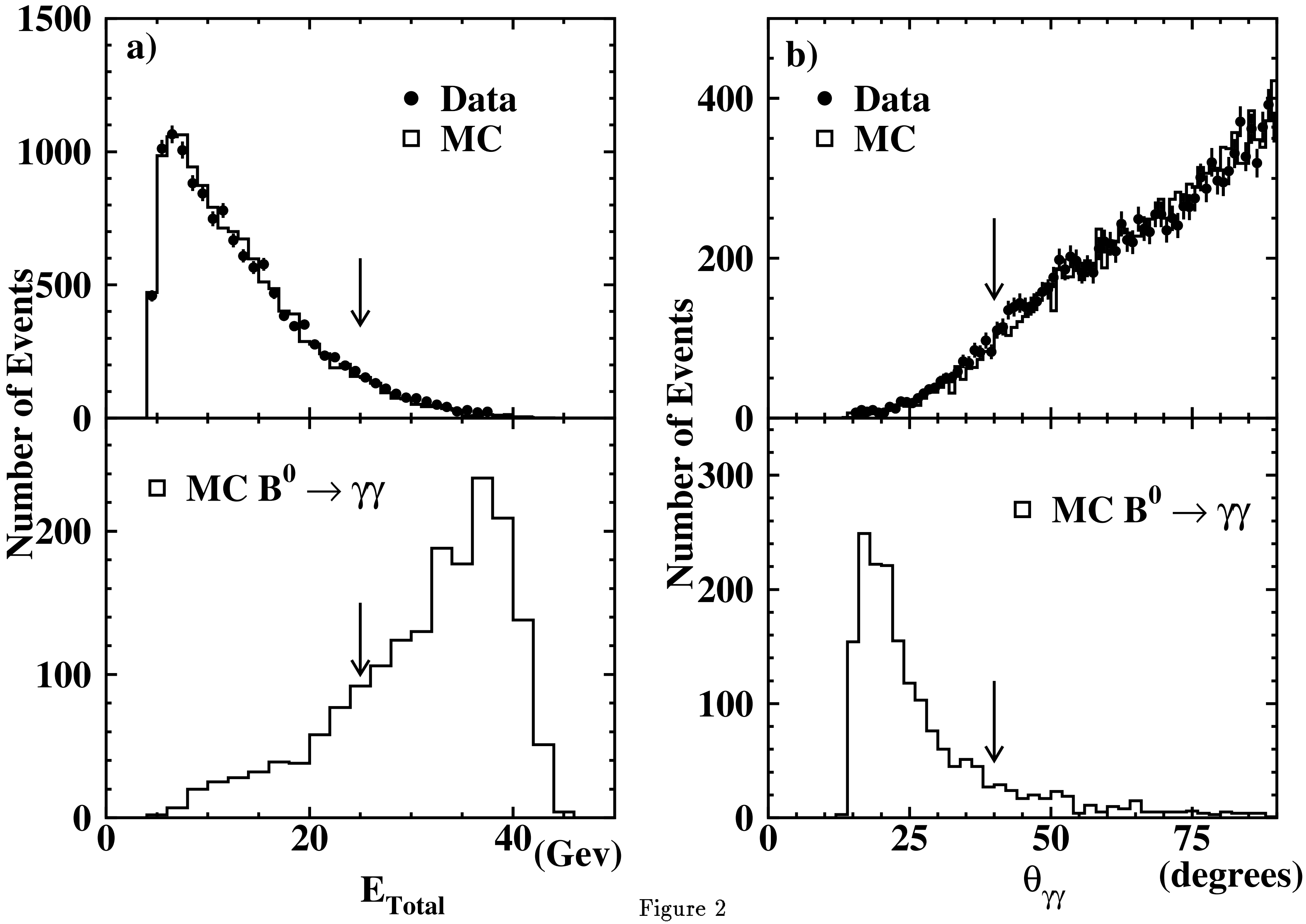
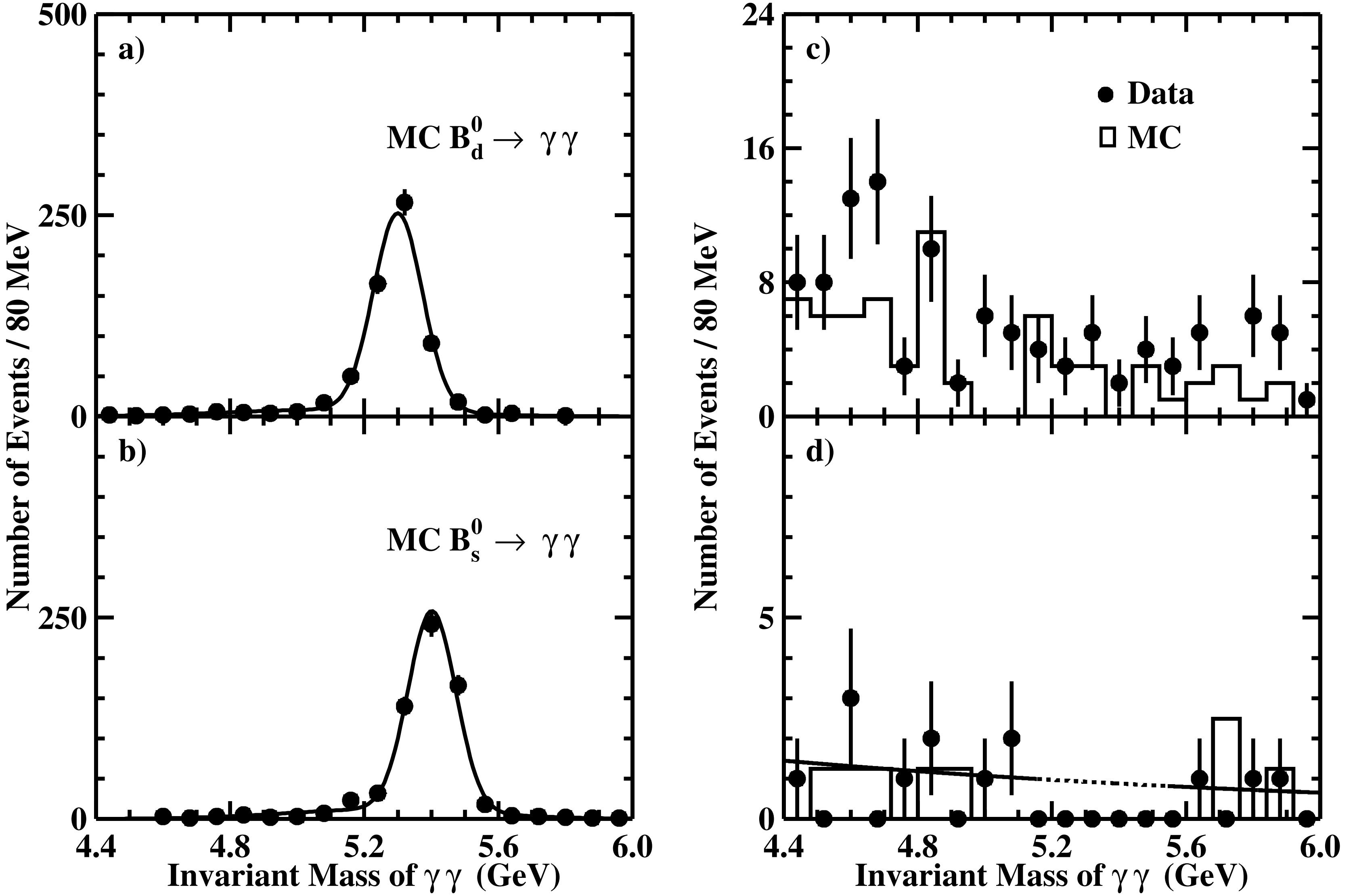

a)
Data
MC
MC $B^0 \to \gamma\gamma$
Number of Events
1500
1000
500
0
200
100
0
0
20
40
(Gev)
E_{Total}
b)
Data
MC
MC $B^0 \to \gamma\gamma$
Number of Events
400
200
0
300
200
100
0
0
25
50
75
(degrees)
$\theta_{\gamma\gamma}$

Figure 2



a)
MC $B_d^0 \to \gamma\gamma$
b)
MC $B_s^0 \to \gamma\gamma$
c)
Data
MC
d)
Number of Events / 80 MeV
Invariant Mass of $\gamma\gamma$ (GeV)
500
250
0
24
16
8
5
4.4
4.8
5.2
5.6
6.0

Figure 3